provide low reflectivity surfaces," and that Braun teaches the formation of triangular-profiled gratings because "gratings exhibit good antireflective properties and very low diffraction efficiency in backward diffracted orders." The Examiner stated further that Braun also teaches a method of forming an anti-reflective coating on the photodetector which "effectively lowers the ORL (optical return loss).

The Examiner then concluded that it would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the method of Zaidi et al. to use a photo detector as disclosed by Braun because increasing the light absorption of a photo detector would improve the efficiency and performance of the photo detector, that it would have been obvious to one having ordinary skill at the time the invention was made to have modified the method of Zaidi et al. to create a grating having a triangular-profiled gratings disclosed by Braun, because the triangular gratings "exhibit good antireflective properties and very low diffraction grating efficiencies in backward diffracted orders," and that it would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the method of Zaidi et al. to form an anti-reflective coating on the grating surface as taught by Braun, because forming an anti-reflective coating on the grating surface "effectively lowers the ORL (optical return loss). Applicant respectfully disagrees with the Examiner concerning this ground of rejection since, as will be set forth hereinbelow, claim 1 has been amended to clearly show that Zaidi et al. teaches away from the present claimed invention and, therefore, has been incorrectly combined with the Braun reference by the Examiner.

The Examiner continued by rejecting claims 4, 5, 7, 11, and 14 were rejected under 35 U.S.C. 103(a) over Zaidi et al. in view of Braun as applied to claims 1-3, 6, 8-10, 12 and 13, and further in view of other cited references. As stated hereinabove, claim 1 has been amended to clearly show that Zaidi et al. teaches away from the present claimed invention, so that the combination of the Zaidi et al. and Braun references is improper. Therefore, since claims 2-14 depend from claim 1, and the deficiency of the subject combination is not

materially affected by the other references cited by the Examiner, applicant believes that no further response is required with regard to the rejection of claims 4, 5, 7, 11, and 14.

Claims 15, 16 and 19 were then rejected under 35 U.S. C. 103(a) as being unpatentable over Ruby et al. ('021) in view of Zaidi et al. and in view of admissions made in the disclosure, since Ruby et al. discloses a method for forming a solar cell with a random-textured surface to increase light absorption, and a method for cleaning the surface of the substrate using a second etching process. The Examiner concluded that it would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the method of Ruby et al. to form a grating on the surface of the solar cell as taught by Zaidi et al. because Zaidi et al. teaches that "for identically etched structures, uniform structures showed an order of magnitude smaller reflectance than random structures." Moreover, the Examiner concluded that it would be obvious to have modified the method of Ruby et al. to form an n-type junction using gas source doping and to form n- and p-electrical contacts on the solar cell because it is well-known in the art, as is disclosed in the subject application, and to use the step of forming a grating using wet chemical etching because Zaidi et al. teach that wet chemical etching to form uniform structures is well-known in the art. Applicant respectfully disagrees with the Examiner concerning this ground of rejection, since claim 15 has been amended to clearly show that Zaidi et al. teaches away from the present claimed invention. As a result, applicant believes that the Examiner has improperly combined Zaidi et al. with Ruby et al. ('021). Additionally applicant believes that no further response is required with regard to the rejection of claims and claims 16 and 19 which depend from claim 15.

Claims 17 and 18 were rejected under 35 U.S.C. 103(a) as being unpatentable over Ruby et al. ('021) in view of Zaidi et al. and admissions made in the disclosure, and further in view of Sakaguchi et al., since although Zaidi et al. does not disclose the method of removing surface damage using wet-chemical etching comprising the step of exposing the surface to KOH and nitric acid solutions, Sakaguchi et al. teach the use of KOH and nitric acid solutions to

perform selective etchings. The Examiner then concluded that it would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the method described by Ruby et al., Zaidi et al. and the admissions of the subject patent application to use KOH and nitric acid solutions to clean the surface damage of the solar cell because KOH and nitric acid solutions will selectively and rapidly etch the surface. Applicant respectfully disagrees with the Examiner concerning this ground of rejection, since claim 15 has been amended to clearly show that Zaidi et al. teaches away from the present claimed invention. As a result, applicant believes that the Examiner has improperly combined Zaidi et al. with Ruby et al. ('021) and Sakaguchi et al. Additionally, applicant believes that no further response is required with regard to the rejection of claims and claims 17 and 18 which depend from claim 15.

Claims 20-24 were rejected under 35 U.S.C. 103(a) as being unpatentable over Ruby et al. ('021) in view of Zaidi et al., in view of Ruby et al. ('280), and in view of admissions made in the subject disclosure, since the Examiner asserted that the '021 patent discloses a method for forming a solar cell with a random-textured surface to increase light absorption, and a method for cleaning the surface of the substrate using a second etching process, and concluded that it would have been obvious to form a grating on the surface of the solar cell as taught by Zaidi et al. because Zaidi et al. teach that "for identically etched structures, uniform structures showed an order of magnitude smaller reflectance than random structures." The Examiner stated that the '280 patent discloses a method for forming a junction using ion implantation of phosphorous, a method for heating the solar cell in an oxygen atmosphere, and concluded that it would have been obvious to have modified the method of the '021 patent to form an n-type junction in a solar cell using ion implantation of phosphorous because forming such a junction would provide a cost-efficient method for forming a solar cell junction in the photo-responsive device, and to anneal the solar cell in an oxygen atmosphere because annealing the solar cell in an oxygen atmosphere can form an anti-reflecting and passivating oxide layer on the solar cell.

Applicant respectfully disagrees with the Examiner concerning this ground of rejection, since claim 20 has been amended to clearly show that Zaidi et al. teaches away from the present claimed invention. As a result, applicant believes that the Examiner has improperly combined Zaidi et al. with Ruby et al. ('021 and '280). Additionally, applicant believes that no further response is required with regard to the rejection of claims and claims 21-24 which depend from claim 20.

Claims 1, 15 and 20 have been amended to more particularly point out the distinguishing features of the present claimed invention. No new matter has been added by these changes, since support for the limitation that a "...greater amount of the incident light entering said photo responsive device propagates more closely to the surface upon which the light is incident than is achieved by a refractive surface, thereby increasing light absorption by said photo responsive device close to the surface upon which light is incident.", derives from among several statements within the subject Specification, as originally filed, that on page 15, lines 3-6, where it is stated that: "Therefore, enhanced absorption, particularly in the near IR region, and <u>close to the surface</u> can be [sic] achieved by designing a grating structure which couples maximum energy into either first, or second diffraction orders propagating at large (> 60°) angles.", and pages 25 and 26 from <u>Fundamentals Of Optics</u> by Francis Arthur Jenkins (McGraw-Hill, Inc., 1976) reproduced in Attachment 2 hereof where it is stated that: "We have already seen in Fig. 2A(a) that as light passes from one medium like air into another medium like glass or water the angle of refraction is always less than the angle of incidence. While a decrease in angle occurs for all angles of incidence, there exists a range of refracted angles for which no refracted light is possible. A diagram illustrating this principle is shown in Fig. 2B, where for several angles of incidence, from 0 to 90°, the corresponding angles of refraction are shown from 0° to ϕ_c, respectively." For silicon, ϕ_c is approximately 15° which means that incident light does not stray far from normal incidence to the surface once the light enters a purely refractive surface.

In summary, for the reasons to be set forth hereinbelow, applicant respectfully believes that Zaidi et al. teaches away from the present invention,

and that the Examiner has improperly combined Zaidi et al. with other cited references in the rejection of claims pending 1-24 under 35 U.S.C. 103(a). Therefore, applicant believes that the Examiner has not met the burden of a *prima facie* obviousness-type rejection. Reexamination and reconsideration are respectfully requested.

Briefly, the present invention includes a method for enhancing light absorption in selective spectral ranges by efficient optical coupling of light into obliquely propagating diffraction orders inside a silicon (Si) substrate. Figure 1 illustrates a grating etched on the front surface of a substrate which is characterized by its period d, linewidth l, and depth h. The light is normally incident and the period is chosen such that no diffraction orders in air are present. Due to symmetric profile, equal energy is coupled into the two ±1-diffraction orders and the two ±2-diffraction orders; the fraction of energy coupled into the first and second orders is a complex function of grating parameters. For improved solar cells, particularly in the space environment, it is desirable that the maximum energy be coupled into those orders propagating nearly parallel to the surface of light incidence; in the present situation, the maximum energy into the two ±2-diffraction orders, and the least energy into the normally propagating zero-order. Additionally, the ±1-diffraction and ±2-diffraction orders are seen to form angles θ_1 and θ_2 respectively, with respect to the surface normal, and that the optical path lengths for these orders are increased by $1/\cos\theta_1$ and $1/\cos\theta_2$ with respect to the zero-order transmitted beam. Thus, for angles, θ, between 30° and 85°, this represents increase in optical path length relative to the zero-order of between approximately 1.15 and 11.5, respectively.

The performance of a solar cell is a critical function of its internal quantum efficiency (IQE), which determines the relative percentage of photo-generated electron-hole pairs (EHPs) lost to recombination after accounting for reflection losses. Therefore, in solar cells, the primary goal is enhancement of light absorption while minimizing recombination losses. Figure 1 hereinbelow shows silicon surface reflectance and absorption depth as a function of wavelength. It is seen that silicon reflectance is high ~ 52 % in the UV, and reduces to ~ 33 % in

most of the visible to near-IR range. The spectral absorption curve shows that most of the UV-Visible (0.3~ 0.6 μm) light is absorbed within ~ 1 μm of the top surface. At longer wavelengths, particularly near the band edge, the absorption is much weaker; that is an absorption depth of ~ 100 μm at 1-μm wavelength. In most of the terrestrial and space solar cells, the top surface p-n junction formed within ~ 0.1-0.5 μm of the surface collects almost 100 % of the photo-generated EHPs in the UV-Visible spectral range. In near-IR range, however, a fraction of EHPs is lost to bulk recombination.

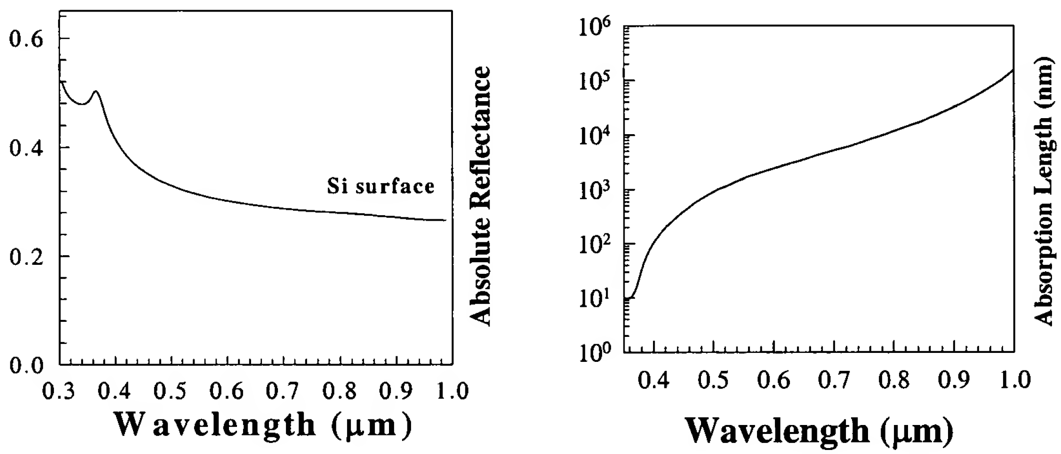

Figure 1. Spectral reflectance (left) and absorption depth (right) plotted as a function of wavelength in Si.

In principle, an optimized stack of thin films can be designed to reduce overall reflection to the ~ 1-10 % range. However, such reflection reduction does not improve near-IR absorption due to lack of scattering of the normally propagating light as shown in Fig. 2. As stated hereinabove, the spectral light, independent of incident angle and wavelength, travels within a narrow cone defined by the critical angle. In order to improve near-IR absorption in conventional and thin-film Si solar cells, light trapping procedures based on geometrical optics considerations have been developed by the present inventor. The trapping procedure of the present invention takes advantage of the fact that due to high refractive index n of Si, light inside Si propagating outside a narrow angular cone defined by the critical angle $\theta_c = \mathrm{Sin}^{-1}(\lambda/n)$ is subjected to total

internal reflection. Therefore, by re-directing light inside Si at oblique angles (> θ_c), total internal reflection causes multiple bounces within the cell enhancing its absorption probability. Detailed statistical analysis has shown that in comparison with a planar sheet, the effective absorption can be enhanced by as much as a factor of $4n^2$. However, in order to reach this statistical limit, surface texture must fully randomize incident light. It has also been reported that optimal texture dimensions needed to achieve this statistical randomization are comparable to light wavelengths inside Si. For Si in the UV-near IR spectral range, this translates to feature sizes in 50-300 nm range. When optical wavelengths are comparable, or smaller than surface features, geometrical optics considerations do not provide a clear picture. Instead an accurate vector modeling of light interaction is required.

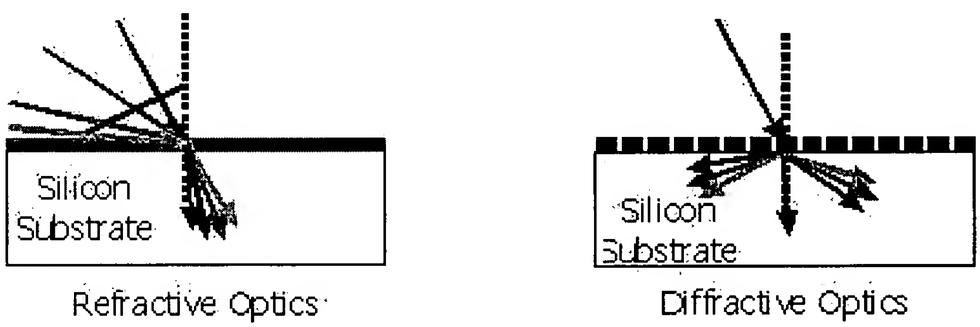

Figure 2. Comparison of refractive (left) and diffractive (right) optics.

Subwavelength surface texturing based on random reactive-ion etching, also referred to as "black Si", consist of either columnar or triangular profiles varying in linewidths, spacing and depths from ~ 50-500 nm, and typically exhibit broadband low-surface reflection for wavelengths < 1 μm of ~ 1-5 %. The nanoscale textures represent a smooth transition, somewhat similar to a graded index film, in refractive index from the incident medium to the bulk Si. The physical mechanism is similar to that of a stack of anti-reflection films, and no scattering enhancement inside the silicon surface is anticipated.

A more uniform patterning capability is expected to provide improved reflection and absorption control. Figure 2(right) illustrates the concept of the present invention. By appropriate selection of grating period and profile, light

scattering in the angular range between 0-90° is achievable, therefore increasing the absorption length by factor of $1/\cos(\theta)$ stated hereinabove. Since for larger values of θ, the electron-hole pairs are also generated closer to the junction, their collection probability is significantly enhanced, leading to superior near IR performance.

Turning now to the rejection of claims 1-3, 6, 8-10, 12 and 13 under 35 U.S.C. 103(a) as being unpatentable over Zaidi et al. in view of Braun et al., and the other rejections which combine Zaidi et al. with other references, applicant wishes to state that the present invention is counter-intuitive in that the grating structure of Zaidi et al. which significantly reduces reflection of light incident on a surface of a substrate does not channel a majority of this light into light propagating substantially obliquely to the surface of incidence. The grating shown in Fig. 2 of Zaidi et al. is characterized by a period of ~ 0.47 μm, grating projections of ~ 0.05 μm, a depth of ~ 1 μm, and a duty cycle of ~ 0.106). Using these parameters, a diffraction efficiency calculation using GSOLVER™ software was performed. This is a similar calculation to that described on pages 15 and 16 of the subject Specification for a duty cycle of .75 and which give rise to Figs. 20a, 20b and 21 of the subject patent application. The results are shown in Attachment 2 of Amendment A filed on July 22, 2002, which illustrates transmitted efficiencies of 0-order, ±1-diffraction, and ±2-diffaction orders for the TM-polarization (note that the calculations in Figures 20a, 20b and 21 are also for the TM polarization). To be observed is that for the grating of Zaidi et al., all of the incident energy is coupled into the normally propagating zero-order, while almost no energy is coupled into obliquely propagating diffraction orders at a depth of 1-μm. Therefore, although the grating of Zaidi et al. is efficient in coupling almost 75% of incident energy into the Si substrate, virtually all of this energy is directed into the zero order.

By contrast, the grating structures of the present claimed invention have thicker projections (that is, projections giving rise to duty cycles of ~ 0.75). Diffraction efficiency calculations for the 0.47-μm period grating with Si projections of ~ 0.35 μm are shown in Figure 2 of Attachment 2 of Amendment A

filed on July 22, 2002. To be noticed is that for the thicker projections (higher duty cycles), significantly greater energy is coupled into obliquely propagating diffraction orders. In this case at a depth of ~ 0.2 μm, ~ 56 % energy is coupled into ±1-diffraction orders, the rest of the energy going into zero-order with almost zero energy into ±2-diffraction orders. This is consistent with the calculations which gave rise to Figs. 20a, 20b and 21 of the subject patent application.

Therefore, the grating structure of Zaidi et al. is designed for reducing reflection; that is, it behaves as an anti-reflection coating, while being substantially unsuitable for the diffractive coupling which is the subject of the claimed invention. In fact, page 13, lines 10-19 and Fig. 18 of the subject Specification, as originally filed, states that the gratings of the present invention may not completely reduce surface reflection from a substrate, and anti-reflection coatings are applied to the grating surface to accomplish this function without interfering with the grating coupling efficiency of the incident light into obliquely propagating modes.

For these reasons, applicant believes that the Zaidi et al. reference teaches away from the subject claimed invention and, therefore, has been improperly combined with the references identified by the Examiner in the rejection of all pending claims under 35 U.S.C. 103(a).

For the reasons set forth hereinabove, applicant believes that claims 1-24, as amended, are in condition for allowance and such action by the Examiner at an early date is earnestly solicited. Reexamination and reconsideration are respectfully requested.

Respectfully submitted,

Date: June 13, 2003

Signature of Attorney

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ATTACHMENT 2

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Fundamentals of Optics

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This book was set in Times Roman.
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2

PLANE SURFACES AND PRISMS

The behavior of a beam of light upon reflection or refraction at a plane surface is of basic importance in geometrical optics. Its study will reveal several of the features that will later have to be considered in the more difficult case of a curved surface. Plane surfaces often occur in nature, e.g., as the cleavage surfaces of crystals or as the surfaces of liquids. Artificial plane surfaces are used in optical instruments to bring about deviations or lateral displacements of rays as well as to break light into its colors. The most important devices of this type are prisms, but before taking up this case of two surfaces inclined to each other, we must examine rather thoroughly what happens at a single plane surface.

2.1 PARALLEL BEAM

In a beam or pencil of parallel light, each ray meets the surface traveling in the same direction. Therefore any one ray may be taken as representative of all the others. The parallel beam remains parallel after reflection or refraction at a plane surface, as shown in Fig. 2A(*a*). Refraction causes a change in width of the beam which is easily seen to be in the ratio $(\cos \phi')/(\cos \phi)$, whereas the reflected beam remains of the same

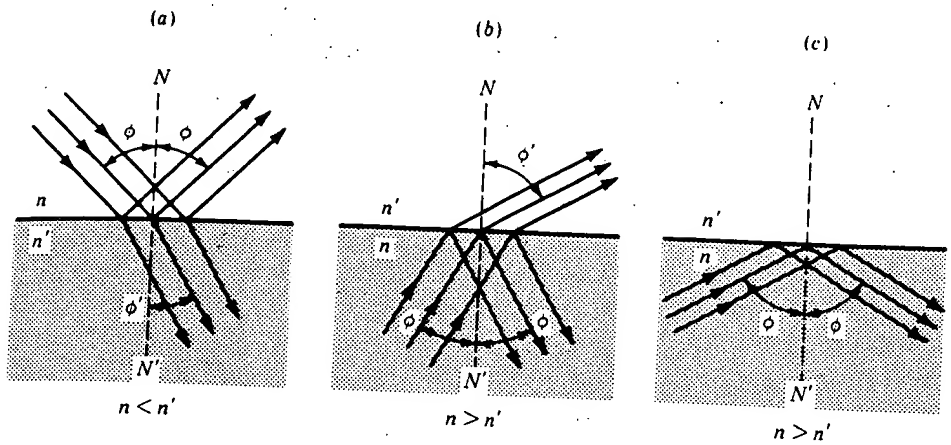

FIGURE 2A
Reflection and refraction of a parallel beam: (*a*) external reflection; (*b*) internal reflection at an angle smaller than the critical angle; (*c*) total reflection at or greater than the critical angle.

width. There is also chromatic dispersion of the refracted beam but not of the reflected one.

Reflection at a surface where n increases, as in Fig. 2A(*a*), is called *external reflection.* It is also frequently termed *rare-to-dense* reflection because the relative magnitudes of n correspond roughly (though not exactly) to those of the actual densities of materials. In Fig. 2A(*b*) is shown a case of *internal reflection* or *dense-to-rare* reflection. In this particular case the refracted beam is narrow because ϕ' is close to 90°.

2.2 THE CRITICAL ANGLE AND TOTAL REFLECTION

We have already seen in Fig. 2A(*a*) that as light passes from one medium like air into another medium like glass or water the angle of refraction is always less than the angle of incidence. While a decrease in angle occurs for all angles of incidence, there exists a range of refracted angles for which no refracted light is possible. A diagram illustrating this principle is shown in Fig. 2B, where for several angles of incidence, from 0 to 90°, the corresponding angles of refraction are shown from 0° to ϕ_c, respectively.

It will be seen that in the limiting case, where the incident rays approach an angle of 90° with the normal, the refracted rays approach a fixed angle ϕ_c beyond which no refracted light is possible. This particular angle ϕ_c, for which $\phi = 90°$, is called the *critical angle.* A formula for calculating the critical angle is obtained by substituting $\phi = 90°$, or $\sin\phi = 1$, in Snell's law [Eq. (1m)],

$$n \times 1 = n' \sin\phi_c$$

● so that

$$\sin\phi_c = \frac{n}{n'} \tag{2a}$$

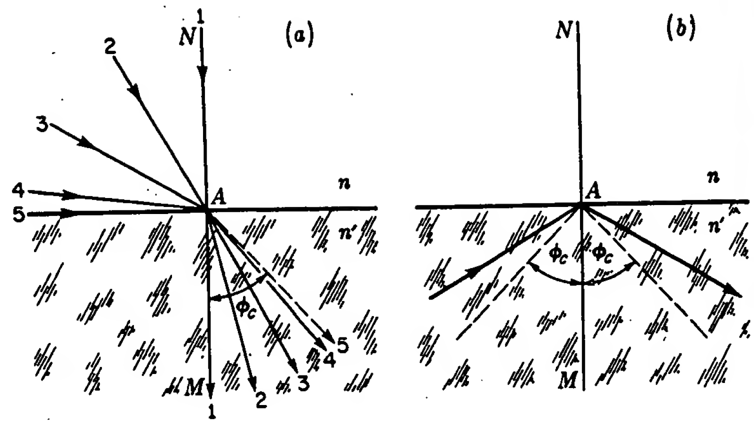

FIGURE 2B
Refraction and total reflection: (*a*) the critical angle is the limiting angle of refraction; (*b*) total reflection beyond the critical angle.

a quantity which is always less than unity. For a common crown glass of index 1.520 surrounded by air $\sin \phi_c = 0.6579$, and $\phi_c = 41°8'$.

If we apply the principle of reversibility of light rays to Fig. 2B(*a*), all incident rays will lie within a cone subtending an angle of $2\phi_c$, while the corresponding refracted rays will lie within a cone of 180°. For angles of incidence greater than ϕ_c there can be no refracted light and every ray undergoes total reflection as shown in Fig. 2B(*b*).

> *The critical angle for the boundary separating two optical media is defined as the smallest angle of incidence, in the medium of greater index, for which light is totally reflected.*

Total reflection is really total in the sense that no energy is lost upon reflection. In any device intended to utilize this property there will, however, be small losses due to absorption in the medium and to reflections at the surfaces where the light enters and leaves the medium. The commonest devices of this kind are called *total reflection prisms*, which are glass prisms with two angles of 45° and one of 90°. As shown in Fig. 2C(*a*), the light usually enters perpendicular to one of the shorter faces, is totally reflected from the hypotenuse, and leaves at right angles to the other short face. This deviates the rays through a right angle. Such a prism may also be used in two other ways which are illustrated in (*b*) and (*c*) of the figure. The Dove prism (*c*) interchanges the two rays, and if the prism is rotated about the direction of the light, they rotate around each other with twice the angular velocity of the prism.

Many other forms of prisms which use total reflection have been devised for special purposes. Two common ones are illustrated in Fig. 2C(*d*) and (*e*). The roof prism accomplishes the same purpose as the total reflection prism (*a*) except that it introduces an extra inversion. The triple mirror (*e*) is made by cutting off the corner of a cube by a plane which makes equal angles with the three faces intersecting at that